Appendix E

Variations in substrate size, and influences of substrate size and immovable objects upon Chinook salmon redd attributes in the Green River, King County, Washington.

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Abstract:

In the Green River, Washington, Chinook salmon spawn in portions of the river subject (upstream) to and not subject (downstream) to dam-induced gravel starvation. Substrate around the redd perimeter was significantly larger in the gravel starved segment than in the non-starved. Redd area was a function of substrate size up to a mean substrate size of approximately 125 mm (r^2=0.34), then redd area became independent of substrate size. No evidence was found that female size influenced redd area. River wide, mean and median redd areas (n=129) were 12.4 and 10.4 $m^{2.}$ Fifty percent of redds were between 6.2 and 17.1m^2. Mean redd area was 14.1 and 6.9 m^2 for unconfined (n=104) and confined (n=30) redds, respectively. Unconfined redds were significantly larger than confined redds.

Two factors influenced redd area: size of substrate into which the redd was dug; and large substrate material (typically >150 mm) that precluded further excavation and produced confined redds. Confined redds were found only in the gravel starved, upper segment. No confined redds were found in the non-starved reach. Substrate size ranged from 10 mm to 480 mm. Mean and median sizes of all sample particles were 82.7 mm and 59.0 mm, respectively. Fifty percent of all sampled particles were between 37.0 and 92.7 mm. Mean and median substrate size around individual redds was 89.2 mm and 61.9 mm. Fifty percent of substrate found around individual redds was between 48.8 and 94.1 mm. respectively.

Introduction

Spawning salmon have particular hydraulic and sedimentary requirements (Crisp and Carling 1989; Montgomery et al. 1999. Understanding these variables is essential to developing management and restoration strategies seeking to improve or restore spawning potential. Furthermore, information on the physical characteristics of Chinook spawning locations and redds is important to ascertaining critical habitats (Crisp and Carling 1989).

Chinook salmon redds can vary considerably in size as noted by Healey (1991), Bjornn and Reiser (1991), and Keeley and Slaney (1996). Despite these observations and warnings (Moyle and Baltz 1985; Greenberg et al. 1996) against using generalized criteria derived from limited studies, regulatory agencies, as well as groups proposing salmon habitat restoration proposals often use generalized redd areas to estimate carrying capacity or escapement goals. Based upon information described by Burner (1951), an area of 20 m^2 (5 m^2 for the actual redd and an additional 15 m^2 for a defended territory) per spawning summer/fall Chinook pair is often used to calculate the number of redds that could be supported by available spawning habitat. The use of a single mean to prescribe the recommended spawning area for salmon implicitly assumes that no intra-basin differences exist in the system for which the escapement goal was developed or is being developed, or that utilized mean redd area is derived from representative differing habitats. However, variation in the required or actual redd area can influence capacity estimates. If too small a redd area is used to determine the escapement goal, then the number of spawners may exceed habitat capacity and cause redd superimposition, leading to egg loss. Too large an area will lead to potentially, under-utilized spawning areas. Five m^2 is often used for the actual redd area, despite more recent studies reporting larger Chinook redd areas: 15.3 m^2 (derived from Hawke 1978); 9.1 and 10.0 m^2 (Neilson and Branford 1983); 17 m^2 (Chapman et al. 1986); and 17.5 m^2 (Deverall et al. 1993).

The Green River, King County, Washington, is a major producer of Chinook salmon in Puget Sound and supports important recreational, commercial, cultural, and subsistence fisheries. Despite the importance of habitat use parameters to the accuracy of both population models and habitat carrying capacity estimates, little basin specific information exists regarding Chinook spawning requirements in the Green River. The only publicly available information concerning Green River Chinook redd area is found in Malcom (2003). He found redds in the upper segment of the mainstem Green River were significantly smaller than redds in a lower segment. Additionally, he found redds in Newaukum Creek, a major tributary to the Green River, were significantly smaller than those in the lower mainstem segment, but similar in size to the upper segment redds. Malcom (2003) did not measure substrate size; however, based upon visual observations he attributed the observed differences in area to the presence of large immovable objects that confined or constrained the area of substrate a Chinook could excavate.

Substrate availability in the Green River has been differentially altered by anthropogenic processes. Howard Hanson Dam has prevented the steam movement of spawning size and larger substrate into the downstream reach of the Green River (Kerwin and Nelson 2000). The result has been a coarsening of the streambed extending progressively downstream (Perkins 1993, 2000; Kerwin and Nelson 2000). It is considered (Kerwin and Nelson 2000) this streambed coarsening or armouring has adversely influenced the spawning of salmonids, such as Chinook and steelhead. To compensate for these adverse impacts, the US Army Corps of Engineers is placing gravel in the Green River to mitigate the loss of spawning substrate from above Howard Hanson Dam. Though this gravel placement is ongoing, no information is available regarding the effectiveness of these measures or if they have any influence upon the redd attributes.

To assist future restoration projects, this study describes the distribution of water depths and surface particle sizes used by spawning fall Chinook in order to: (1) document the size of gravel used by spawning Chinook in reaches subject and not subject to gravel starvation and supplementation; (2) determine if substrate size influences redd attributes such as area, depth, etc; (3) ascertain if intra-basin differences in redd area and substrate size exist; and (4) determine if intra-basin differences existed in fish size that could account for differences in redd area.

Methods and Study Area

Study Area

The Green/Duwamish River (Green River) drains to the Puget Sound basin of Washington State (Figure 1a). The Green River has a mainstem length of 151 km and drains a basin of 1275 km^2.

Chinook salmon spawn throughout the entire accessible portion of the Green/Duwamish River above River Kilometre (Rkm) 41.2, as well as the major tributaries, such as Soos and Newaukum Creeks (Kerwin and Nelson 2000; WDFW and WWTIT 1994). Chinook spawning occurs from mid-September through the end of October, with a peak in early October (WDFW and WWTIT 1994; Kerwin and Nelson 2000). In addition to Chinook, coho (*O. kisutch*), chum (*O. keta*), pink (*O. goburscha*), sockeye (*O. nerka*), and steelhead (*O. mykiss*) spawn in the study area. Excepting chum salmon and steelhead, Chinook spawning partially overlaps in time and space with the other species.

Little is known regarding the temporal and spatial extent of pink spawning in the Green River. However, pink salmon in the nearby White River system, a former tributary to the Green River, spawn from mid-September through early November (WDFW and WWTIT 1994). In the Green River, pink salmon spawn both in the disturbed substrate within Chinook redds and the undisturbed substrate adjacent to Chinook redds (pers. obsn.). However, since Green River pink salmon spawn only in odd years (WDFW and WWTIT 1994), no pink salmon spawned during this study. Coho spawn throughout the Green River from early November to late January (WDFW and WWTIT 1994; Kerwin and Nelson 2000). Consequently, there is little overlap in time, except towards the end of Chinook spawning. However, there is considerable overlap in both river reach location (pers. obsn.) and site-specific redd location (pers. obsn). Similar to pink salmon, coho spawn in and adjacent to Chinook redds. A small population of sockeye spawn in the Green River primary above the Green River Gorge. These sockeye spawn during the early part of the Chinook spawning and apparent sockeye redds with holding sockeye are often seen next to Chinook holding on redds (pers. obsn). Steelhead spawn throughout the river from March to May (WDFW and WWTIT 1994). Though they do not overlap in time, steelhead redds are often seen in the same locations as Chinook redds from the previous year and Chinook redds are often seen next to flagging marking steelhead redds from the spring (pers. obsn.).

Tacoma Public Utilities (TPU) operates a water diversion dam at RKm 99 that blocks the upstream passage of adult salmonids to historical spawning habitat. Upstream of this water diversion dam, the US Army Corps of Engineers (Corps) operates Howard Hanson Dam, a water storage and flood control dam at Rkm 104. Since the early 1960s, Howard Hanson Dam has blocked the downstream movement of all gravel, reducing gravel supply and storage in downstream reaches (Kerwin and Nelson 2000). This blockage or starvation of downstream gravel below has influence substrate composition to at least Rkm 73 (Perkins 1993; Perkins 2000), a point 31 km downstream of HHD and reducing the availability of spawning gravel (Kerwin and Nelson 2000). Substrate in areas influenced by gravel starvation is comprised of a higher percentage of larger substrate than found in the unaffected downstream reaches. Analysis of substrate sizes reported in Caldwell and Hirschey (1989) indicates reaches in the non starved area contain 41% cobble and 54% gravel compared to 66% cobble and 27% gravel in the starved areas.

The Corps has undertaken a series of restoration projects in the reach between the TPU Diversion Dam and the upstream extent of the Green River Gorge, an area greatly influenced by gravel starvation. These projects include: (1) placement of gravel berms containing spawning size substrate in 2003 and 2004 with the intent that high river flows distribute this gravel into spawning patches: (2) construction of wood jams to provide stable spawning areas and create holding areas; and (3) placement of loose large and small wood into locations where it will be naturally transported and distributed by the river.

Methods

Two river segments separated by 30 km were chosen for the study: one downstream (Fig. 1b) and one upstream segment (Fig 1c). These two segments represent major spawning areas upstream and downstream of the Green River gorge (Kerwin and Nelson 2000; Malcom 2003). The 3.4 km long upstream segment is subject to Howard Hanson Dam-induced gravel starvation, while the 2.0 km long downstream segment is not. Each segment was subdivided into smaller reaches based upon channel configuration and the location of restoration activities (Fig. 1b, 1c, Table 1) to permit comparisons of substrate size and redd dimensions within segments. Surveys were to commence in mid-September and be conducted weekly until the end of November, when Chinook spawning typically ceases.

The river was walked by an observer wearing polarized glasses. The observer moved downstream in a zig-zag pattern, water depths permitting, to visually inspect as much of the wetted width as possible. Overlooking upland features were also used to spot redds. Upon encountering a possible redd, the observer inspected the redd to determine if it was a Chinook redd. Only redds judged to be completed by a well defined tailspill and pit (Schmetterling 2000) were measured. Redd location was recorded non-differentially with a Garmin GPS. Redds occupied by salmon of other species were excluded from data recording. Redds superimposed upon another redd (greater than 50% overlap in length or width) were not measured for dimensions, but locations and other information were recorded.

Water depth was measured immediately upstream of and adjacent to the redd over undisturbed gravel (Schmetterling 2000). Water depth upstream of the redd, and water depths over the pit and the tailspill crest were measured to the nearest cm. Mound length and total length were measured from the upstream edge of the redd excavation to the middle of the tailspill crest and the downstream extent of excavated substrate, respectively. Redd width was measured across the redd mid-point. Redd length and width were measured to the nearest dm. The minimum potential depth to which salmon had excavated substrate below the streambed was determined by subtracting redd water depth from pit depth. Distance from left bank and wetted width were measured to the nearest m. Distance to left bank was measured from the redd centre. If a specific attributed could not be determined, it was not recorded.

Substrate composition was determined using a modified Wolman pebble-count method (Wolman 1954) around the redd perimeter were conducted to determine surface substrate size. However, since this study sought to determine the influence of gravel and larger substrate size upon redd area, no effort was made to sample fines that could be readily excavated and transported downstream in the current. Following Rennie and Miller (2000), the pebble count was performed at 0.5 m intervals in the undisturbed substrate immediately adjacent to the disturbed substrate. With the eyes averted, a hand was lowered into the water column and the first pebble encountered retrieved (Pasternack et al. 2004). If surface fines were present, the finger was pushed through till it encountered granular material. The pebble counts extended from the upstream edge of the redd downstream to where the tailspill mound rose above the original streambed. In most cases, samples taken at or adjacent to redds are considered to represent substrate used by spawning salmon (Kondolf 2000). Particles were measured along their median axes (that smallest axis that fits through a sieve) to the nearest mm using calipers.

If there was no physical constraint upon the ability of a female to excavate gravel, the redd was considered unconfined. If large, immovable objects are found along three edges of the redd, the redd was considered confined. Confined redds are conceptually similar to pocket gravels within boulder dominated channels reported by Kondolf (2000).

If orange flagging denoting a steelhead redd marked by the WDFW during the spring of 2004 was observed next to a Chinook redd, this was noted.

Fish size was compared between survey segments by measuring to the nearest mm, the length (mid-eye to hypural bone) and body depth.

Data Analysis

The size of particles used by salmon was determined using two metrics of mean and median size. To determine the range of substrate sized used by spawning Chinook, each individual sample particle (individual) regardless of what redd it came from was analyzed. To ascertain relationships between substrate size and redd parameters, all particles removed from each individual redd were pooled into a single mean value (pooled) that was considered representative of mean or median substrate size at that particular redd location. The following definitions are used: (1) collective redds – all redds in the study area, regardless of location or degree of confinement; (2) individual particle size – measurements based upon the size distribution of all sampled particle as modified by a location identifier; and (3) pooled redd particle size– mean size of all particles sampled at a single redd as modified by a location identifier.

Results were calculated for each segment and reach using SigmaStat (SPSS 1997) and Microsoft Excel. Descriptive statistics for substrate composition were derived for both individual and pool substrate sizes. Descriptive statistics for the individual particles provide a more detailed description of the distribution of substrate sizes encountered by spawning Chinook, while the pooled sizes more accurately reflects the influence of substrate size upon various redd attributes. Frequency histograms were used to describe distributions of depth, substrate size, redd area, etc. Upstream and downstream segments were compared to each other. Unless otherwise indicated comparisons between segments or among reaches were compared by the Mann-Whitney test. Within segment reaches were compared to other within segment reaches as well as reaches from the other segments. Reported redd areas are based upon area to the end of the tailspill, rather than the area upstream of the mound crest. An estimate of potential substrate sizes used by steelhead was derived by separating analysing Chinook redds adjacent to known steelhead redds.

Descriptive characteristics will calculated for the study area, upstream and downstream segments, reaches within segments, and confined and unconfined redds. No attempt was made to produce preference curves or adjust for habitat use compared to habitat availability.

Results

Substrate composition for entire study area

Collective redds

Substrate was sampled from 125 redds, 61 from the lower segment and 64 from the upper (Table 2, Figs 1c and 1d). Of the 125 sampled redds, 94 redds were unconfined and 31 confined. No confined redds were found in the lower segment. Lower segment mainstem redds were spread across the river width, though considerable clumping occurred (pers. obsn). However, upper segment mainstem redds tended towards the lateral margins of the river, except where mid-channel bars were found, whether natural or created such as the log jams in the Corps Interbar (CIB) reach. In total, 1163 individual particles were sampled, 642 and 508 from the lower and upper segments, respectively (Table 3).

Mean and median individual particle sizes were 82.7 mm and 59.0 mm, respectively (Table 3, Fig. 2). Fifty percent of individual particles were between 37.0 and 92.7 mm (Fig 2, Table 4). Mean and median pooled substrate size was 89.2 mm and 61.9 mm, respectively (Fig 2a). Fifty percent of pooled substrate was between 48.8 and 94.1 mm, respectively. The size distributions of all sampled substrate particles are shown in Fig. 3. Size distributions of individual particles sampled from the upstream and downstream segment are shown in Fig. 4. Cumulative percent substrate size distributions for the study area and the upper and downstream segments are shown in Fig 5. Very little substrate was less than 20 mm in size.

Unconfined and confined redds

Mean individual particle size was 57.7 mm and 166.5 mm for the unconfined (n=922) and confined (n=228) redds, respectively (Table 4a). Median individual particle size was 52.0 and 174.5 mm for unconfined and confined redds, respectively. Individual particles from unconfined redds were significantly smaller (P=<0.001 than those from confined redds. Fifty percent of the individual substrate from unconfined redds were between 35.0-74.0 mm, compared to 74.0-227.5 for confined redds.

Unconfined redds (n=94) pooled particle mean and median substrate size were 60.5 and 56.8 mm, respectively (Table 4). Confined redds (n=31) pooled particle mean and median 176.3 and 185.7 mm, respectively. Pooled substrate size from unconfined redds were significantly smaller (P=<0.001) than confined pooled substrate. Fifty percent of the pooled substrate from unconfined redds was between 45.7-72.4 mm, compared to 125.8-231 for confined redds.

<u>Redd Area and attributes for entire study area</u>

<u>Collective Redds.</u>

As not all parameters could be extracted from each sampled redd, the sample sizes varies among redd parameters. Histograms of redd area for the study area and the upper and lower segments are shown in Fig 6. Distribution of redd water depths and pit depths are shown in Figs 7 and 8, respectively. Mean and median redd area (n=129) was 12.4 and 10.4 m^2, respectively (Table 5). Fifty percent of redds were between 6.2 and 17.1m^2 (Table 5). Mean and median redd depths (n=132) were 40.5 and 38.0 cm, respectively (Table 6). Fifty percent of redds were found in water 29.0 to 50.0 cm deep. Mean and median pit depths (n=123) were 13.6 and 12.0 cm, respectively. Fifty percent of redd pits were between 7.0 and 17.0 cm deep (n=66).

Unconfined versus confined redds

Mean redd area was 14.1 and 6.9 m^2 for unconfined (n=104) and confined (n=30) redds, respectively (Table 8). Median redd areas were 12.7 and 6.3m^2, respectively. Unconfined redd area was significantly larger (P<0.001) than that of confined redds. Fifty percent of unconfined and confined areas were between 7.5-18.9 and 5.1-9.0 m^2, respectively.

Chinook redds near old steelhead redds.

Measurements of gravel were taken from 16 Chinook redds located next to old steelhead redds. Mean pooled substrate size was 52.5 mm with a standard deviation of 13.3 mm.

Female Chinook size

No significant differences existed between female length or depth between the upstream or downstream segments.

<u>Substrate composition differences between upstream and downstream segments</u>

Collective Redds

Mean individual particle sizes were 55.0 mm and 110.0 mm for the lower (n=642) and upper (n=508) segments, respectively (Table 3). Median individual particle sizes were 51.0 mm and 77.0 mm, respectively. Fifty percent of the lower segment individual particles were 33.0-71.0 mm in size, compared to 42.0-170.0 mm in the upper segment (Fig. 2, Table 3). Individual particles from the lower segment was significantly smaller (P<0.001) than those from the upper. Mean pooled particle sizes were 57.5 mm and 119.5 mm for the lower (n=61) and upper (n=64) segments, respectively (Table 2, 4a). Median pooled particle sizes were 54.6 mm and 89.9 mm, respectively (Table 2. 4a). Fifty percent of the lower segment pooled particles were 44.1-68.7 mm in size compared to 56.5-173.6 in the upper segment. Lower segment pooled substrate size was significantly smaller (P<0.001) than the upper.

Unconfined versus confined redds

Mean individual particle size for unconfined redds were 55.0 mm (n=642) and 64.0 mm (n=280) for lower and upper segments, respectively (Table 4b). Median individual particle size for unconfined redds were 51.0 and 55.5 mm for lower and upper redds (Table 4b). Individual particles from lower segment unconfined redds were significantly smaller (P=0.006) than those from the upper segment unconfined redds. Fifty percent of the individual particles from unconfined redds were between 33.0-71.0 mm and 37.0-80.0 mm for the lower and upper segments, respectively (Table 4a). No confined redds were found in the lower segment, therefore no comparisons can be made.

Redd areas and attributes

Redd Area

Mean redd area for all redds was 17.6 and 8.45 m^2 for lower (n=56) and upper (n=73) segment redds, respectively (Table 5). Median redd areas were 16.5 and 7.6 m^2, respectively (Table 5). Collectively, lower segment redds were significantly larger than upper segment redds (P<0.001). Fifty percent of collective lower and upper redds were between 12.4-20.3 and 4.7-10.1 m^2, respectively. The relative distribution of redd areas between the upper and lower segments is shown in Fig. 6. Unconfined lower redds at 17.6 m^2 were significantly larger (P=<0.001) than unconfined upper redds at 7.1 m^2. There was no significant difference in redd area between confined and unconfined upper redds (P=0.215).

Unconfined versus confined redds

Mean redd area was 14.1 and 6.9 m^2 for unconfined (n=104) and confined (n=30) redds, respectively. Median redd area was 12.7 and 6.3m^2, respectively. The area of unconfined redds was significantly larger than that of confined redds (P<0.001). Fifty percent of unconfined and confined areas were between 7.5-18.9 and 5.1-9.0 m^2, respectively. Lower unconfined redds were considerably larger than upper confined and unconfined redds (Table 8a).

Other redd parameters

Mean water depth for lower (n=62) and upper segment redds (n=70) were 16.6 and 14.4 cm, respectively (Table 12). Median water depths for lower and upper redds were 36.0 and 40.0 cm, respectively (Table 13). Water depths did not vary significantly between lower and upper redds (P=0.224). Mean pit depth for lower (n=62) and upper redds (n=70) were 16.6 and 14.4 cm, respectively. Median pit depth for lower and upper redds were 13.0 and 11.0 cm, respectively. Lower segment pit depths were significantly deeper than upper segment pits (P=0.040). This is likely a function of substrate size, though there is most likely so much variation due to other factors that does not show up in a regression. Fifty percent of lower and upstream pit depths were found between 10.0-19.2 and 6.0 and 15.0 cm, respectively.

Redd attributes versus substrate composition

Redd area was inversely related to substrate size (Figs 9 and 10). There was no relationship between water depth and redd length, width, or area. There was no relationship between redd area and pit depth (Fig 11), or redd water depth (Fig 12). Pit depth was independent of redd water depth (Fig.13).

Though redd area was inversely influenced by substrate size, this relationship did not continue beyond mean perimeter substrate size of approximately 125 mm (Fig 9). For mean particle sizes below 125 mm, redd area was related (Fig 10) to mean substrate size (r^2=0.34)

Variation among reaches

Considerable variation in substrate size was observed among the various reaches (Figs 14, 15, 16, and 17). Descriptive statistics for pooled and individual substrate size for confined and unconfined redds for each reach are presented in Tables 4c-4f. Though the larger substrate was found in the upstream reach, substrate size did not uniformly increase in the upstream direction. Patches of smaller size gravel and hydraulic complexing features that stored smaller gravel created a mosaic of smaller and larger gravel. Median gravel sizes for each reach in increasing size are presented in Tables 11a, 11b, and 11c. Based upon individual particles, the smallest substrate was found in the Metzler area and the largest in the Corps Side Channel. Median substrate size of redds between the two Corps' logjams, an area of gravel placement and storage, also tended to be small. However, this smaller gravel was often found among a matrix of larger material. Observed substrate size is small in the Corp Above reach, even though not influenced by restoration projects, due to a mid-channel gravel bar acting as a flow obstruction trapping smaller substrate. Furthermore, high flows during the survey season prevented the sampler from moving into the deeper areas on other side of the mid-channel bar, areas likely of greater substrate size. However, it appeared that most of the spawning in this reach was among the smaller material.

In the lower segment, individual particle size was greater in the Metzler reach than the Metzler Side Channel reach ($P<0.001$); however pooled substrate size did not differ ($P = 0.101$) between the Metzler (n=53) and Metzler Side Channel (n=8) reaches. The Metzler reach is a mainstem channel segment and has greatly flows that the side channel. In the absence of obstructions, surface particle size increases with increasing stream energy. It is expected that in segment of similar slope and geology, that that reach with the greater energy will have larger substrate. Additionally, the Metzler side channel has grown considerably over the last few years due to channel erosion and it may have a smaller cross-section to substrate input ratio than the mainstem and thus have a proportionately greater input of gravel that would again tend to reduce gravel size.

<u>Redd areas</u>

Metzler redds (n=49) at 18.6 m^2 were significantly larger ($P = 0.018$) than Metzler side channel redds (n=7) at 10.6 m^2 and significantly larger than those found in all upper segment reach (Table 5). However, MSC redd area did not differ ($P = 0.185$) from the CIB redds (8.2 m^2). CIB redd areas were significantly larger ($P = 0.015$ and $P = 0.003$) than C03 reach redds (5.1 m^2) and CABOVE redds (4.1 m^2), respectively. CBELOW and CSC did not differ ($P = 0.858$) in size and CBELOW did not differ ($P = 0.543$) from CIB. CBELOW redds (8.3 m^2) were significantly larger ($P = 0.006$ and ($P = <0.001$) larger than C03 redds (4.1 m^2) and CABOVE redds (4.1 m^2), respectively. Only two redds were found in the area immediately adjacent and downstream of the gravel berm placed in 2004. Due to the small sample size, no conclusions could be drawn. It is likely limited spawning occurred in this location due to high water velocities existing in these areas during spawning.

Discussion

Chinook salmon are reported to spawn in gravel with median sizes from 10 mm to 70 mm, with an overall median of approximately 35 mm based upon a literature survey by Kondolf and Wolman (1993). Unfortunately, it is not possible from Kondolf and Wolman's survey to determine the upper size range of spawning substrate. My results are similar for the low end of suitable substrate, but my mean and medians of 89.2 and 61.9 mm, respectively are considerably larger than those reported by Kondolf and Wolman (1993). However, my observed values are not unknown in the literature. Groves and Chandler (1999) reported that approximately 16% of the Chinook in their study area in the Columbia River spawned in dominant/subdominant substrate from 5.1-7.5 and 7.6-15.0 cm, respectively and 5% in 7.6-15.0 and 15.1-22.5 cm, respectively.

There was a paucity of particles smaller than 20 mm and none smaller than 10 mm. This is partially an artefact of the methodology, since fines were not sampled, but also reflects the observation that with some exceptions, there was little observed fine sediment and sand in the surface layers. Additionally, the lack of smaller particles would reflect the fact that Chinook salmon do not spawn in fines or smaller gravel.

Most previous studies reported spawning gravel size distributions as dominant and sub-dominant classes (Kondolf 2000), sizes often estimated. My study reported the actual size for each collected particle, enabling ready comparison to sediment sizes reported in geomorphic literature, and provides a more precise estimate of substrate size upon redd area. Furthermore, excluding large material from sampling may be a source of variability (Kondolf and Wolman 1993). This study reduced the possibility of such variability by including all material larger than fines.

It is considered that female size directly (van de Berghe and Gross 1984; Bjornn and Reiser 1991; Keeley and Slaney 1996) and substrate size inversely (Burner 1951; Deveral et al. 1983) influence redd area. However, such descriptions have been qualitative, rather than quantitative (Kondolf and Wolman 1993). My study confirmed previous qualitative assessments (as reported in Kondolf and Wolman 1993) that redd area was inversely related to substrate size, but did show quantitatively, rather than qualitatively.

There was no observed difference in female size between the upstream and downstream segments. Though female size is considered to influence redd area (Crisp and Carling 1989), the reported wide spread in spawning gravel size versus fish length (Kondolf and Wolman 1993) indicates a female of a given size can spawn in a wide range of substrate sizes. It is unlikely that female size is responsible for the observed differences in redd area, when substrate size can explain much of the difference.

The area of redds constructed in spawning patches with pooled perimeter redd substrate size exceeding approximately 125 mm were independent of perimeter substrate size. It is concluded this represents two factors influencing redd area: (1) size of substrate excavated by salmon; and (2) size of material at which encountering the salmon ceased digging. The breakdown in the relationship between redd area and substrate size for substrates greater than 125 mm arises from the fact that once a particle is immovable, it can no longer exert an incremental effect.

Since redd area is inversely related to substrate size, restoration potential or habitat carrying capacities should consider substrate size. Furthermore, given the variability in redd area observed between the upper and lower segment, basin-wide averages should not be used to determine carrying capacity. This study clearly shows that generic spawning habitat particle size distribution curves generated from samples gathered throughout a basin may not be applicable throughout the entire basin.

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Table 1. Description of survey segments and reaches.

Segment	Reach	Description	Abvn
Lower			
	Metzler	Mainstem Green River reach of 2000 m. Historically large numbers of Chinook and steelhead have spawned in this reach.	M
	Metzler side channel	Right bank side channel to Meztler reach. Side channel is approximately 1000 m long. Over the past ten years, this side channel has grown in size and represents an area of natural habitat formation due to river erosion of banks.	MSC
Upper			
	Corps below	This 1,800 reach includes both mainstem and side channel units. This reach represents habitats not influenced by wood placement and presumably downstream of the area influenced by gravel displaced from the upstream restoration sites.	CBELOW
	Corps side channel	Left bank side channel with its entrance at the downstream end of the downstream gravel bar/wood jam constructed by the US Army Corps of Engineers. This approximately 300 m reach was a non-target reach for restoration, but gravel from the restoration projects could enter this reach.	CSC
	Corps interbar	Reach between the downstream extent of the downstream gravel bar/wood jam and the upstream extent of the upstream gravel bar/ wood jam constructed by the US Army Corps. This reach of approximately 100 m represents a restoration area influenced by constructed wood jams and placed gravel and well as an area downstream of the gravel placed in 2003.	CIB
	Corps 2003 gravel	The reach (1) between the downstream distribution of gravel arising from the 2004 placement and the upstream extent of the upstream constructed gravel bar/wood jam and (2) the main stem between the river associated with the left bank side channel. This 850 m long reach is considered to be most likely influenced by gravel placed in 2003.	C03
	Corps 2004 gravel bar	The area influenced by gravel placed by the Corps in 2004. This area includes both bar created by the placed gravel and the downstream extent of displaced cover	CGB04
	Corps above	Reach between the upstream extent of the gravel placed by the Corps in 2004 and the TPU pipeline crossing. This 400 m long reach would represent areas not influenced by the Corps restoration project.	CABOVE

Table 2. Descriptive statistics for pooled perimeter substrate size for all redds

Location	Size	Missing	Mean	Std Dev		
ALL	125	0	89.2	64.3		
ALL - LOWER	61	0	57.5	16.2		
ALL - UPPER	64	0	119.5	77.4		
M	53	0	56.2	16.5		
MSC	8	0	66.2	10.8		
CBELOW	21	0	108.5	64.8		
CSC	6	0	205.8	92.1		
CIB	17	0	106.5	76.6		
C03	4	0	210.2	106.1		
CGB04	1	0	0.000	--	--	--
CABOVE	16	0	92.800	43.966	10.992	23.4

Location	Range	Max	Min	Median	25%	75%
ALL	274.1	304.0	29.9	61.9	48.8	94.1
ALL - LOWER	65.7	95.6	29.9	54.6	44.1	68.7
ALL - UPPER	271.8	304.0	32.2	89.9	56.7	173.6
M	65.7	95.6	29.9	51.5	43.8	67.9
MSC	32.6	76.6	44.0	67.8	61.8	75.05
CBELOW	216.1	248.3	32.2	103.7	49.1	157.9
CSC	259.2	304.0	44.8	227.9	161.5	268.6
CIB	228.7	274.3	45.6	59.7	56.4	142.8
C03	241.9	301.4	59.5	240.0	138.9	281.6
CGB04	0.000	0.000	0.00	0.000	0.000	0.000
CABOVE	182.9	231.3	48.4	82.9	66.9	100.3

Table 3. Descriptive statistics for all individual particle sizes presented for the entire study area, segments, and reaches.

Segment/reach	**Size**	**Missing**	**Mean**	**Std Dev**
ALL	1163	0	82.7	75.2
ALL LOWER	642	0	55.0	27.5
ALL UPPER	508	0	110.0	88.8
METZLER	565	0	53.5	27.0
METZLER SC	77	0	66.0	28.7
CBELOW	185	0	98.0	74.4
CSIDEC	34	0	214.1	100.6
CIB	142	0	98.5	87.0
CORPS03	30	0	188.1	113.8
CABOVE	117	0	92.5	70.1

	Range	**Max**	**Min**	**Median**	**25%**	**75%**
ALL	470	480	10	59.0	37.0	92.7
ALL LOWER	166	176	10	51.0	33.0	71.0
ALL UPPER	468	480	12	77.0	42.0	170.0
METZLER	166	176	10	50.0	32.0	69.0
METZLER SC	135	147	12	62.0	45.0	84.2
CBELOW	348	360	12	68.0	39.5	151.0
CSIDEC	426	440	14	215.0	175.0	280.0
CIB	468	480	12	62.0	41.0	126.0
CORPS03	351	380	29	195.0	80.0	300.0
CABOVE	425	440	15	77.0	44.0	111.0

Table 4a. Summary information for substrate size for collective substrate taken from both segments.

Substrate size (mm) for lower and upper segments	Mean	Median	25%	75%
Individual – lower	55.0	51.0	33.0	71.0
Individual – upper	110.0	77.0	42.0	170.0
Pooled – lower	57.5	54.6	44.1	68.7
Pooled – upper	119.5	89.9	56.5	173.6

Table 4b. Summary information for substrate size for collective substrate taken from both segments.

Substrate size (mm) for entire study area.	Mean	Median	25%	75%
Individual – all	82.7	59.0	37.0	92.7
Pooled – all	89.2	61.9	48.8	94.1
Individual unconfined – all	57.7	52.0	35.0	74.0
Pooled unconfined – all	60.5	56.8	45.7	72.4
Individual confined – all	166.5	174.5	74.0	227.5
Pooled confined –all	176.3	185.7	125.8	231.0

Table 4c. Descriptive statistics for pooled perimeter substrate size of unconfined redds

Column	Size	Missing	Mean	Std Dev
ALL	94	0	60.5	18.34
ALL - LOWER	61	0	57.4	16.19
ALL - UPPER	33	0	66.2	20.86
M	53	0	56.2	16.53
MSC	8	0	66.2	10.84
CBELOW	8	0	52.4	13.95
CSC	1	0	44.8	--
CIB	10	0	61.5	19.93
C03	1	0	0.0	--
CGB04	1	0	0.0	--
CABOVE	14	0	78.9	18.58

Column	Range	Max	Min	Median	25%	75%
ALL	86.6	116.5	29.9	56.8	45.7	72.4
ALL - LOWER	65.7	95.6	29.9	54.6	44.1	68.7
ALL - UPPER	75.1	116.5	41.4	59.0	49.2	82.8
M	65.7	95.6	29.9	51.5	43.8	67.9
MSC	32.6	76.6	44.0	67.8	61.8	75.0
CBELOW	43.2	84.6	41.4	48.7	44.0	53.8
CSC	0.0	44.8	44.8	44.8	44.8	44.8
CIB	70.9	116.5	45.6	57.2	55.8	59.7
C03	0.0	0.0	0.0	0.0	0.0	0.0
CGB04	0.0	0.0	0.0	0.0	0.0	0.0
CABOVE	61.9	110.3	48.4	79.60	64.8	93.6

Table 4d. Descriptive statistics for pooled perimeter substrate sizes for confined redds

Column	Size	Missing	Mean	Std Dev
ALL	31	0	176.3	75.24
ALL - LOWER	0	0	0.000	--
ALL - UPPER	31	0	176.3	75.24
M	0	0	0.000	--
MSC	0	0	0.000	--
CBELOW	13	0	143.0	59.05
CSC	5	0	237.9	53.29
CIB	7	0	170.7	82.85
C03	3	0	260.5	41.56
CGB04	1	0	0.000	--
CABOVE	3	0	146.2	84.85

Column	Range	Max	Min	Median	25%	75%
ALL	271.8	304	32.2	185.7	125.8	230.9
ALL - LOWER	0.000	0.0	0.0	0.0	0.0	0.0
ALL - UPPER	271.8	304.0	32.2	185.7	125.8	230.9
M	0.0	0.0	0.0	0.0	0.0	0.0
MSC	0.0	0.0	0.0	0.0	0.0	0.0
CBELOW	216.1	248.3	32.2	145.4	113.6	187.2
CSC	142.5	304.0	161.5	230.0	209.6	277.4
CIB	223.9	274.3	50.4	196.7	99.7	233.6
C03	83.1	301.4	218.3	261.7	229.1	291.4
CGB04	0.0	0.0	0.0	0.0	0.0	0.0
CABOVE	169.7	231.3	61.6	145.6	82.6	209.8

Table 4e. Individual unconfined substrate size

Column	Size	Missing	Mean	Std Dev
ALL	922	0	57.7	31.58
ALL LOWER	642	0	55.0	27.46
ALL UPPER	280	0	63.9	38.78
METZLER	565	0	53.5	26.98
METZLER SC	77	0	66.0	28.65
CBELOW	82	0	51.1	23.86
CSIDEC	4	0	44.7	40.06
CIB	88	0	60.9	36.76
CORPS03	11	0	59.4	23.23
CABOVE	95	0	79.2	46.99

Column	Range	Max	Min	Median	25%	75%
ALL	270	280	10	52	35	74
ALL LOWER	166	176	10	51	33	71
ALL UPPER	268	280	12	55	37	80
METZLER	166	176	10	50	32	69
METZLER SC	135	147	12	62	45	84
CBELOW	115	127	12	46	33	68
CSIDEC	89	103	14	31	19	70
CIB	248	260	12	54	37	72
CORPS03	70	99	29	52	39	80
CABOVE	265	280	15	72	42	104

Table 4f. Individual confined substrate size

Column	Size	Missing	Mean	Std Dev
ALL	228	0	166.5	99.74
ALL LOWER				--
ALL UPPER	228	0	166.5	99.74
METZLER				--
METZLER SC				--
CBELOW	103	0	135.4	79.71
CSIDEC	30	0	236.6	82.90
CIB	54	0	159.7	108.42
CORPS03	19	0	262.6	67.81
CABOVE	22	0	150.0	114.10

Column	Range	Max	Min	Median	25%	75%
ALL	463	480	17.000	174.5	74.0	227.5
ALL LOWER						
ALL UPPER	4630	480	17	174.5	74.0	227.5
METZLER	0	0	0	0.0	0.0	0.0
METZLER SC	0	0	0	0.0	0.0	0.0
CBELOW	343	360	17	148.0	64.0	190.7
CSIDEC	385	440	55	230.0	190.0	280.0
CIB	458	480	22	170.0	49.0	230.0
CORPS03	230	380	150	270.0	202.5	310.0
CABOVE	412	440	28	93.5	62.0	220.0

Table 5. Descriptive statistics for redd area.

Column	Size	Missing	Mean	Std Dev
ALL	129	0	12.44	8.39
ALL - LOWER	56	0	17.64	8.43
ALL - UPPER	73	0	8.45	5.80
M	49	0	18.64	8.30
MSC	7	0	10.65	5.97
CBELOW	22	0	11.01	7.20
CSC	7	0	8.90	2.13
CIB	17	0	8.21	2.89
C03	7	0	5.07	1.90
CGB04	2	0	22.77	13.24
CABOVE	18	0	5.09	2.82

Column	Range	Max	Min	Median	25%	75%
ALL	39.03	39.78	0.75	10.420	6.232	17.148
ALL - LOWER	38.14	39.78	1.64	16.515	12.445	20.255
ALL - UPPER	31.38	32.13	0.75	7.550	4.748	10.105
M	35.88	39.78	3.90	17.290	13.515	21.475
MSC	15.74	17.38	1.64	13.010	5.150	14.600
CBELOW	27.63	30.97	3.34	8.300	6.080	12.630
CSC	7.10	12.29	5.19	8.990	8.285	9.723
CIB	9.22	12.83	3.61	7.590	6.045	10.655
C03	4.42	7.61	3.19	4.140	3.377	6.975
CGB04	18.73	32.13	13.40	22.765	13.400	32.130
CABOVE	10.05	10.80	0.75	4.070	3.300	7.020

Table 6. Descriptive statistics for redd depth.

Column	Size	Missing	Mean	Std Dev
ALL	132	0	40.5	15.53
ALL - LOWER	62	0	39.1	16.64
ALL - UPPER	70	0	41.8	14.47
M	54	0	40.1	16.71
MSC	8	0	32.4	15.50
CBELOW	21	0	43.2	16.73
CSC	7	0	31.9	8.69
CIB	16	0	38.7	9.26
C03	7	0	45.1	18.0
CGB04	2	0	27.000	12.73
CABOVE	17	0	47.412	13.91

Column	Range	Max	Min	Median	25%	75%
ALL	76	86	10	38	29.0	50.0
ALL - LOWER	76	86	10	36	28.0	50.0
ALL - UPPER	62	80	18	40	30.0	50.0
M	71	86	15	36	28.0	50.0
MSC	44	54	10	34	18.5	44.5
CBELOW	60	78	18	39	29.7	56.5
CSC	25	45	20	28	26.5	38.0
CIB	35	61	26	37	32.5	44.0
C03	52	72	20	45	30.7	57.0
CGB04	18	36	18	27	18.0	36.0
CABOVE	57	80	23	48	38.7	58.2

Table 7 Descriptive statistics for pit depth.

Column	Size	Missing	Mean	Std Dev
ALL	123	0	13.6	8.89
ALL - LOWER	57	0	14.4	6.95
ALL - UPPER	66	0	12.8	10.27
M	49	0	13.8	6.88
MSC	8	0	18.0	6.68
CBELOW	20	0	10.4	5.70
CSC	7	0	14.61	18.02
CIB	15	0	10.7	7.80
C03	4	0	19.0	15.05
CGB04	2	0	11.5	9.19
CABOVE	18	0	15.3	11.36

Column	Range	Max	Min	Median	25%	75%
ALL	52	54	2	12.0	7.0	17.0
ALL - LOWER	28	30	2	13.0	10.0	19.2
ALL - UPPER	52	54	2	11.0	6.0	15.0
M	28	30	2	13.0	10.0	17.2
MSC	19	28	9	18.5	12.0	23.0
CBELOW	21	24	3	10.0	6.0	14.0
CSC	51	54	3	7.0	6.0	15.5
CIB	29	31	2	11.0	3.2	15.0
C03	34	41	7	14.0	10.0	28.0
CGB04	13	18	5	11.5	5.0	18.0

CABOVE	50	54	4	13.0	7.0	17.0

Table 8 Descriptive statistics for unconfined and confined redd dimensions

Column	Size	Missing	Mean	Std Dev
Mound Length (c	30	0	3.28	0.819
Mound Length (u	105	0	4.39	1.495
Spill Length (c	30	0	4.24	1.044
Spill Length (u	104	0	5.63	1.887
Width (con)	32	0	2.01	0.419
Width (uncon)	108	0	2.98	1.183
Spill Area (con	30	0	6.89	2.378
Spill Area (un)	104	0	14.13	8.652

Column	Range	Max	Min	Median	25%	75%
Mound Length (c	3.2	4.9	1.7	3.450	2.6	3.8
Mound Length (u	8.1	9.1	1.0	4.30	3.4	5.4
Spill Length (c	3.8	6.2	2.4	4.30	3.4	4.9
Spill Length (u	9.6	10.8	1.2	5.80	4.2	6.9
Width (con)	1.50	2.8	1.3	2.10	1.7	2.4
Width (uncon)	7.5	8.3	0.8	2.85	2.20	3.6
Spill Area (con	7.59	10.80	3.2	6.28	5.120	8.99
Spill Area (un)	39.03	39.78	0.70	12.73	7.545	19.00

Table 8a. Median redd area (m^2) segregated into upper and lower segments and confinement

Location/confinement	Median	Range	Min	Max	25%	75%
Upper confined	7.02	7.46	3.34	10.80	5.15	9.01
Upper unconfined	8.06	31.37	0.75	32.13	4.91	12.30
Lower unconfined	16.51	38.14	1.64	39.78	12.45	20.256

Table. 11a. Relative order of substrate size for all redds based upon median individual particle size. Size increased among reaches in the following order. Symbols are defined as follows: < or > denotes a significant difference between reaches with P- value displayed and ~ denotes no significant difference.

M	<	MSC	~	CBELOW	~	CIB	~	CABOVE	<	CORPS03	~	CSC
	<0.001		0.084		0.889		0.472		<0.001		0.447	
50		62		68		62		77		195		215

Table 11b. Relative order of substate size for all redds based upon median pooled particle sizes.

M	<	CIB	~	MSC	<	CABOVE	~	CBELOW	<	CSC	~	C03
	0.003		0.997		0.003		.794		0.008		1	
51.5		59.7		67.8		82.9		103.7		227.8		240

Table. 11c. Relative order of substrate size for unconfined redds based upon median individual particle size.

CBELOW	~	M	~	C03	~	CIB	~	MSC	~	CABOVE
	0.560		0.31		.759		0.062		0.144	
46		50		52		54		62		72

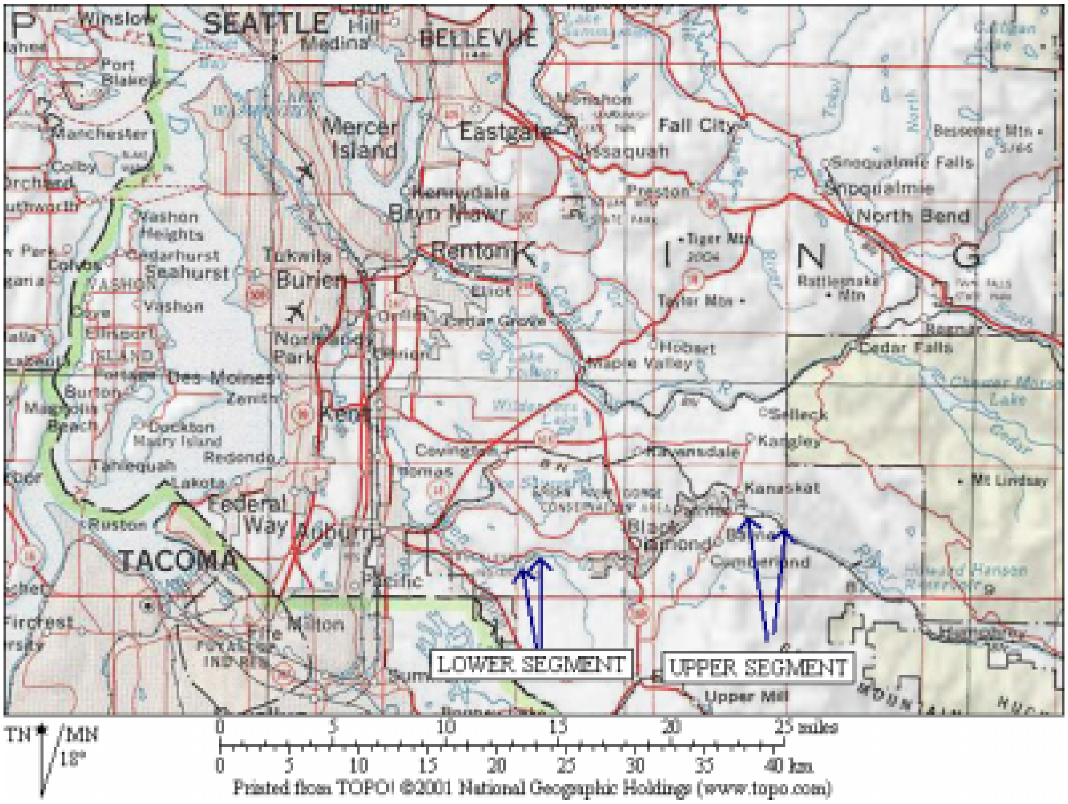

Fig. 1a. Vicinity map showing upstream and downstream segments.

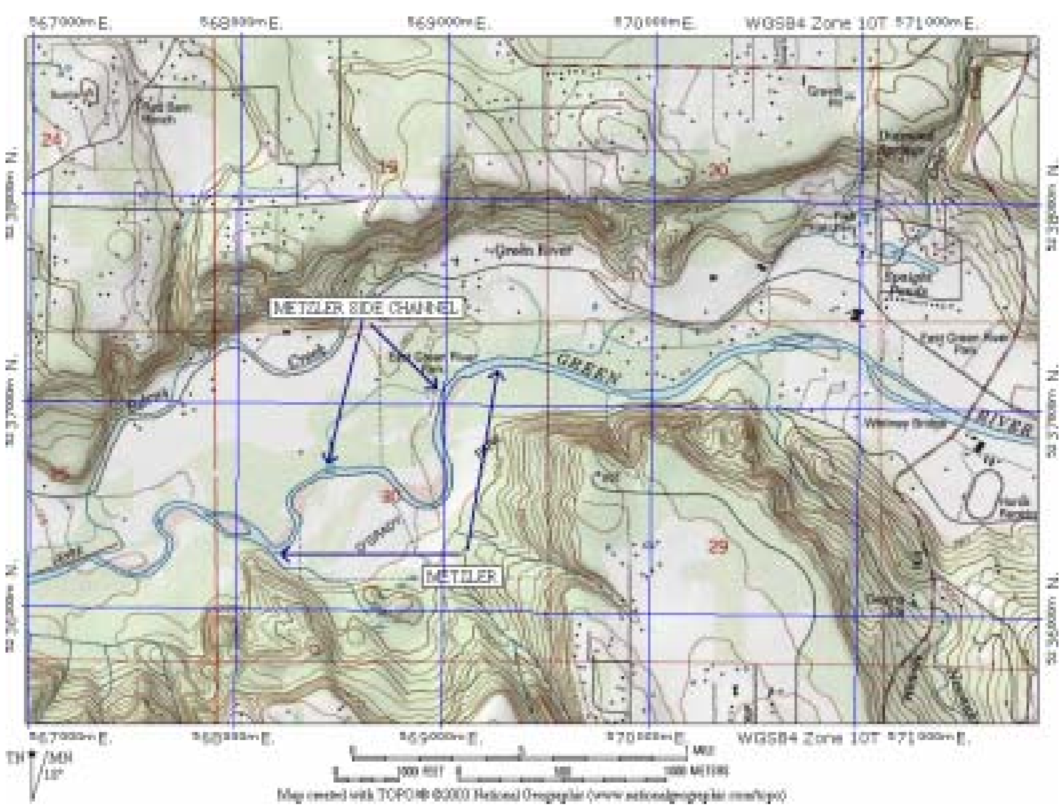

Fig. 1b. Lower segment reaches.

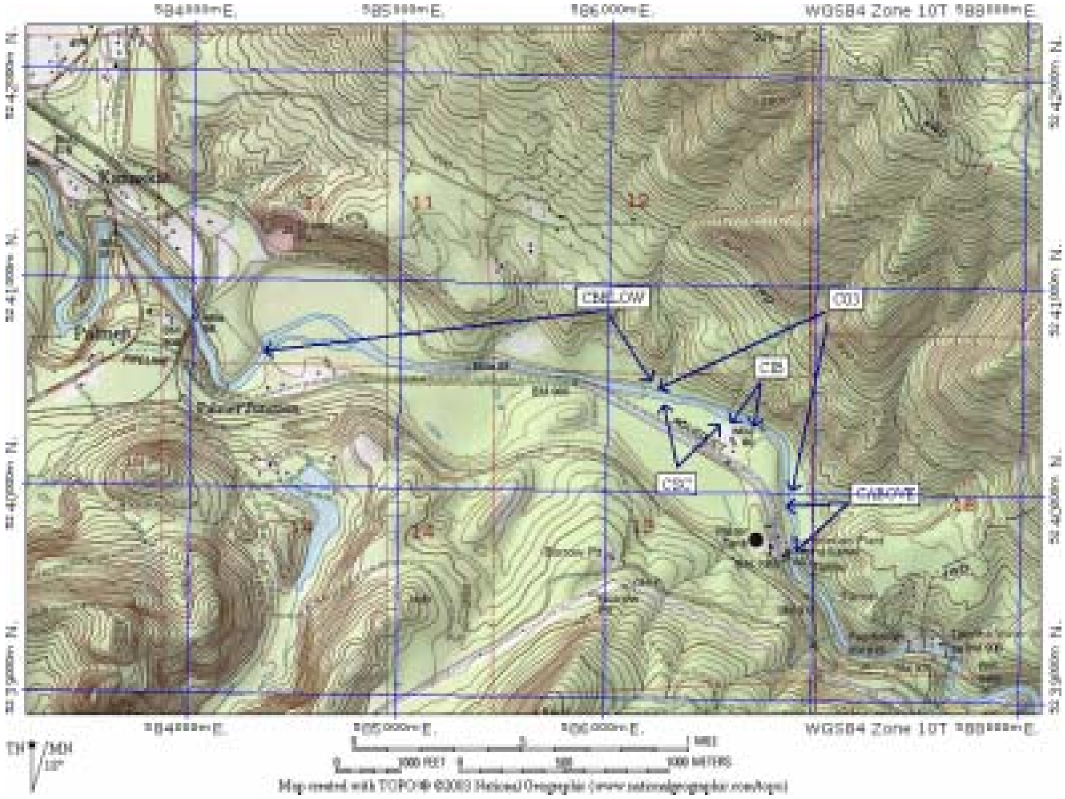

Fig. 1c. Upper segment reaches

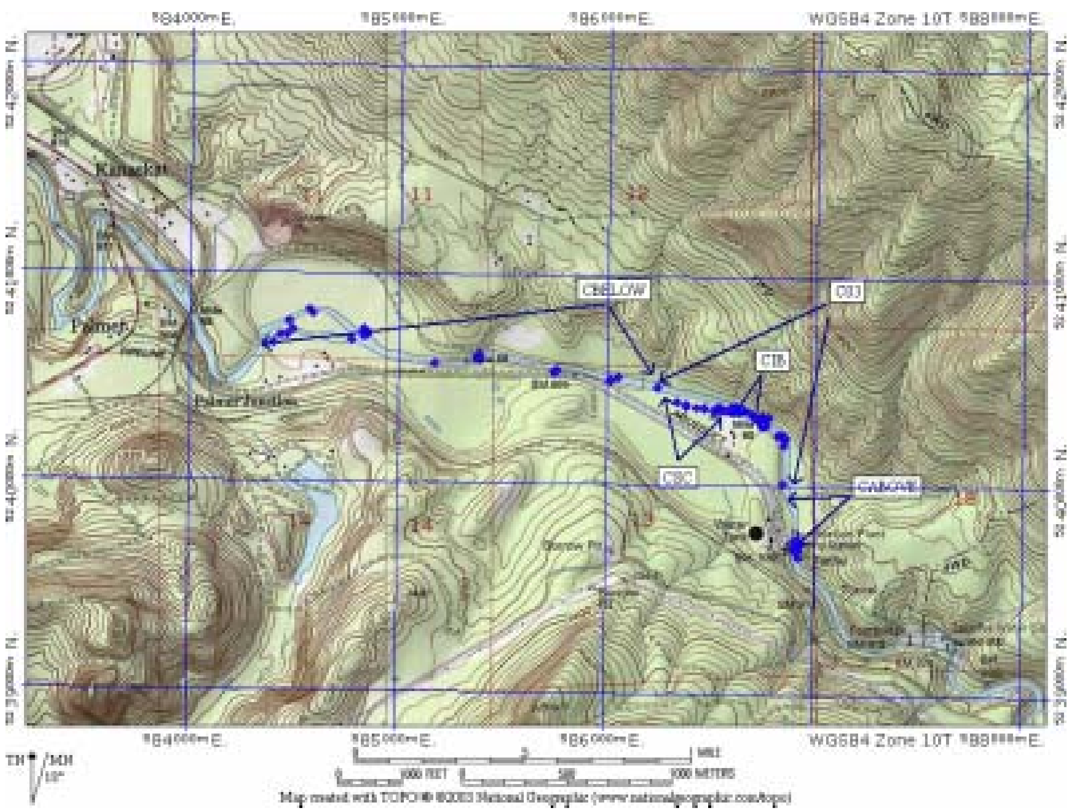

Fig. 1c. Location of upper segment redds.

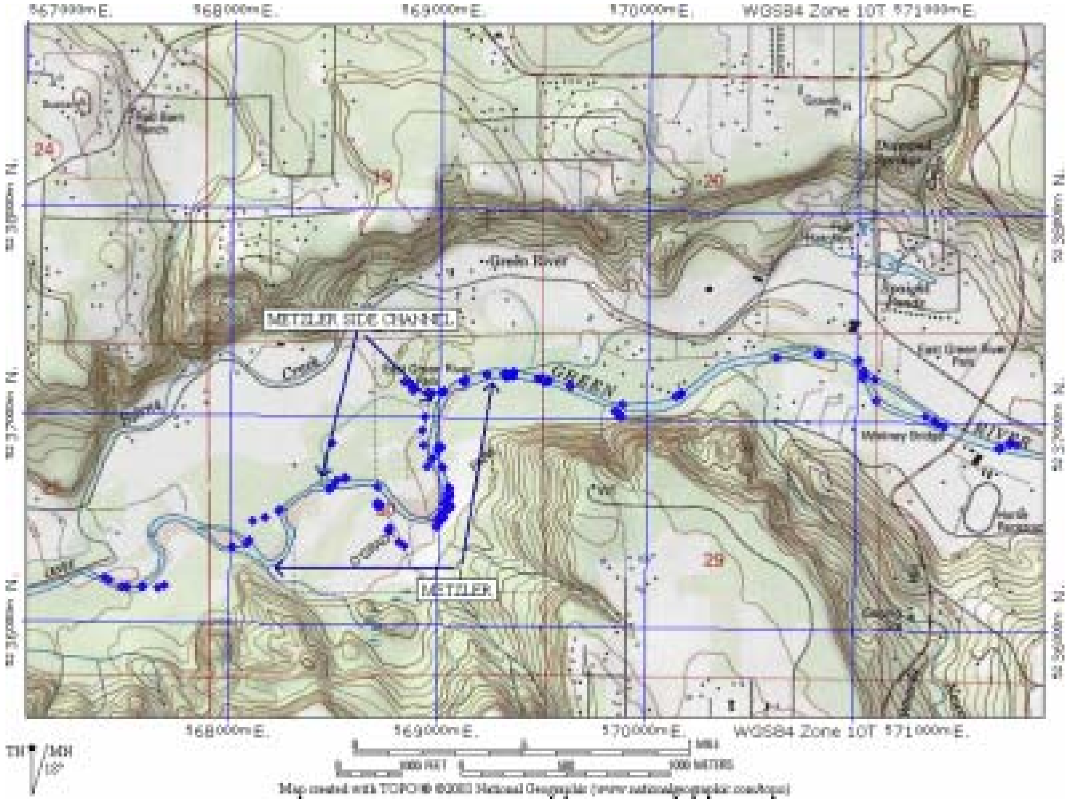

Fig. 1d. Location of lower segment redds. Redds were located outside of the survey reach to gain a better understanding of the relative distribution of redds within the lower segment.

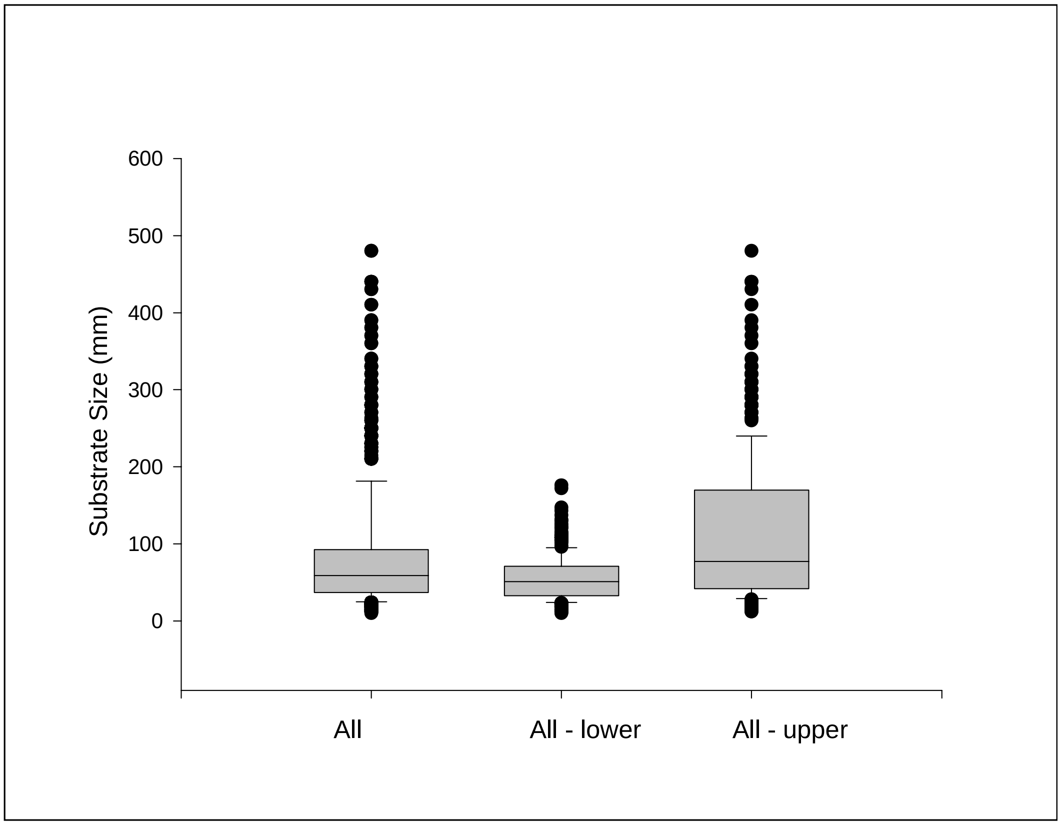

Fig. 2. Individual particle size distribution for entire study area (all) and the upper and lower segment.

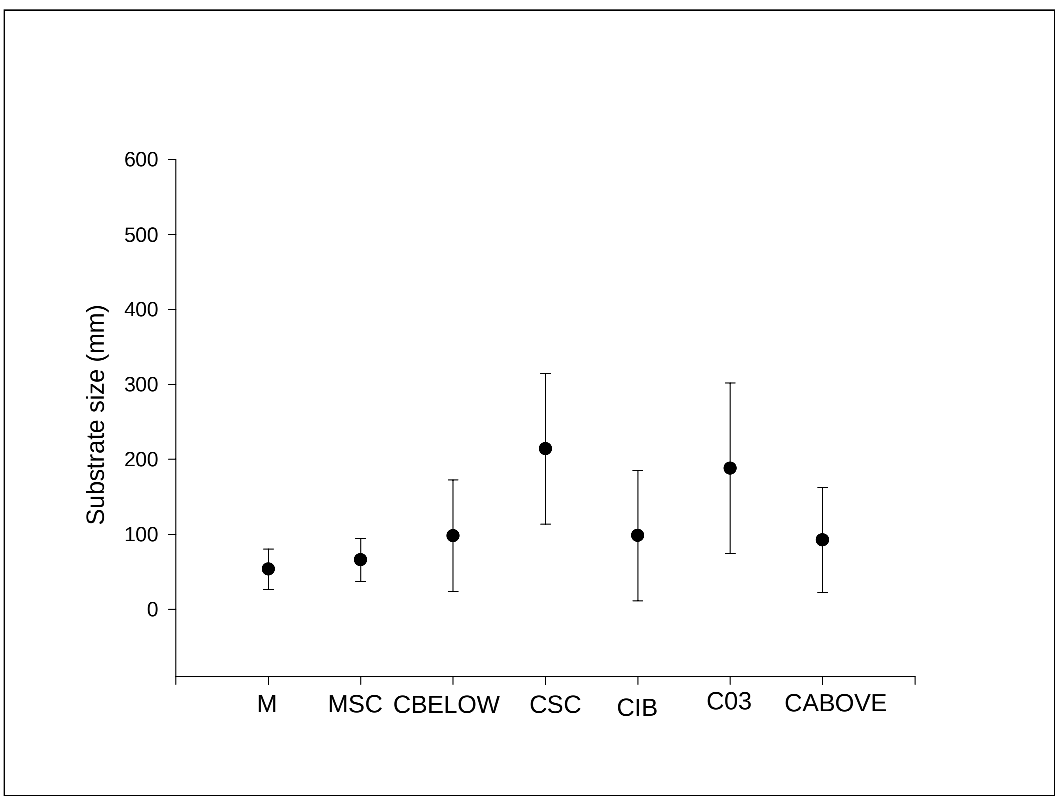

Fig. 2a. Pooled mean individual particle substrate size for various reaches.

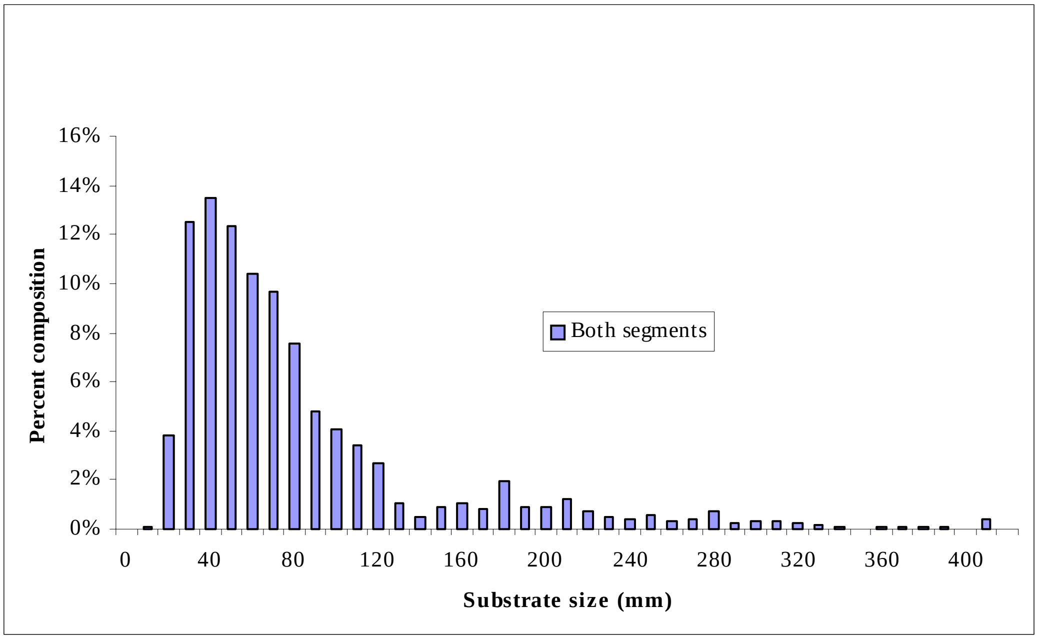

Fig 3. Histogram showing relative size distribution in 10 mm increments of all individual particles sampled during the study.

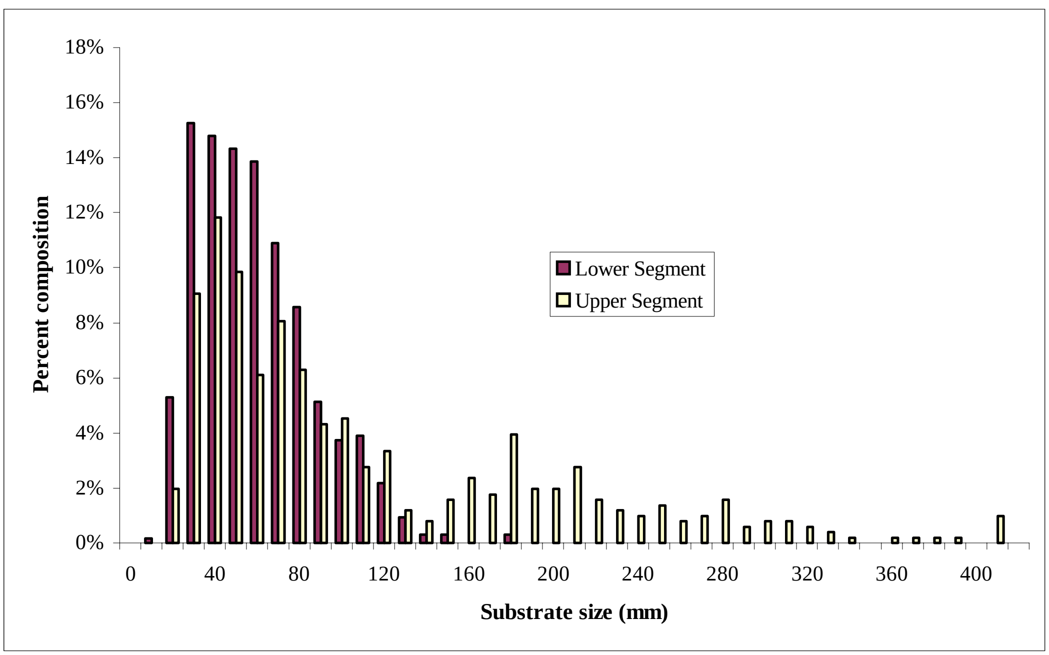

Fig 4. Histogram showing relative size distribution of all individual particles in 10 mm increments for the lower and upper segments. Note both are skewed towards the smaller size categories, but the upper segment has a considerably longer tail towards the large sizes.

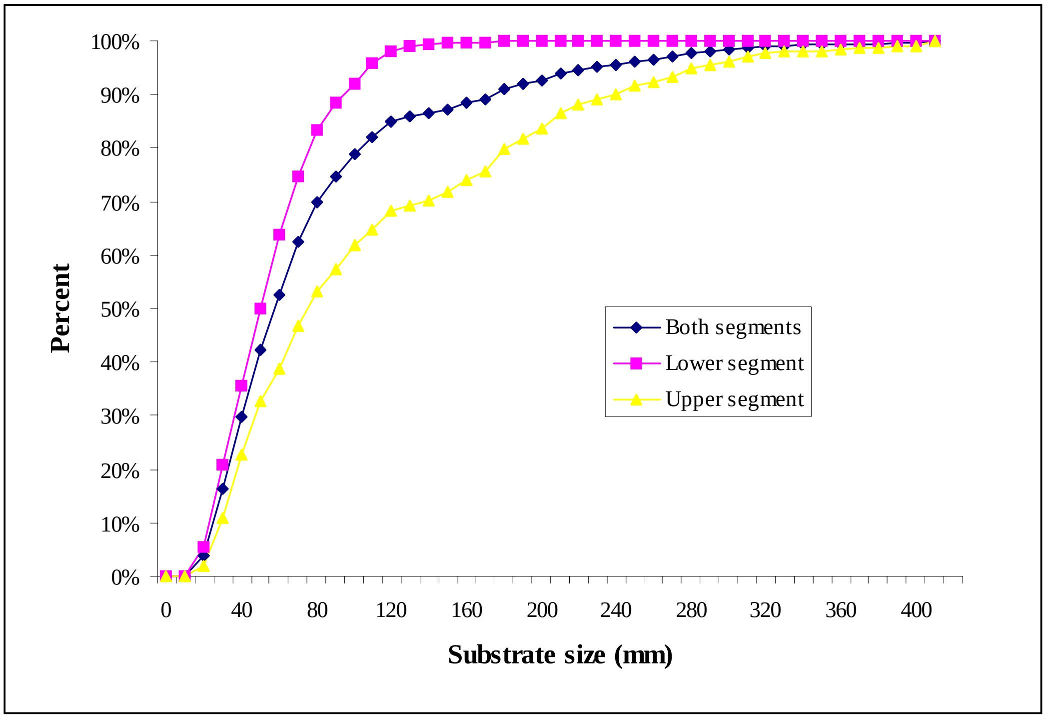

Fig 5. Cumulative contribution of different substrate size categories in 10 mm increments of individual particle size distribution for entire study area, lower segment, and upper segment.

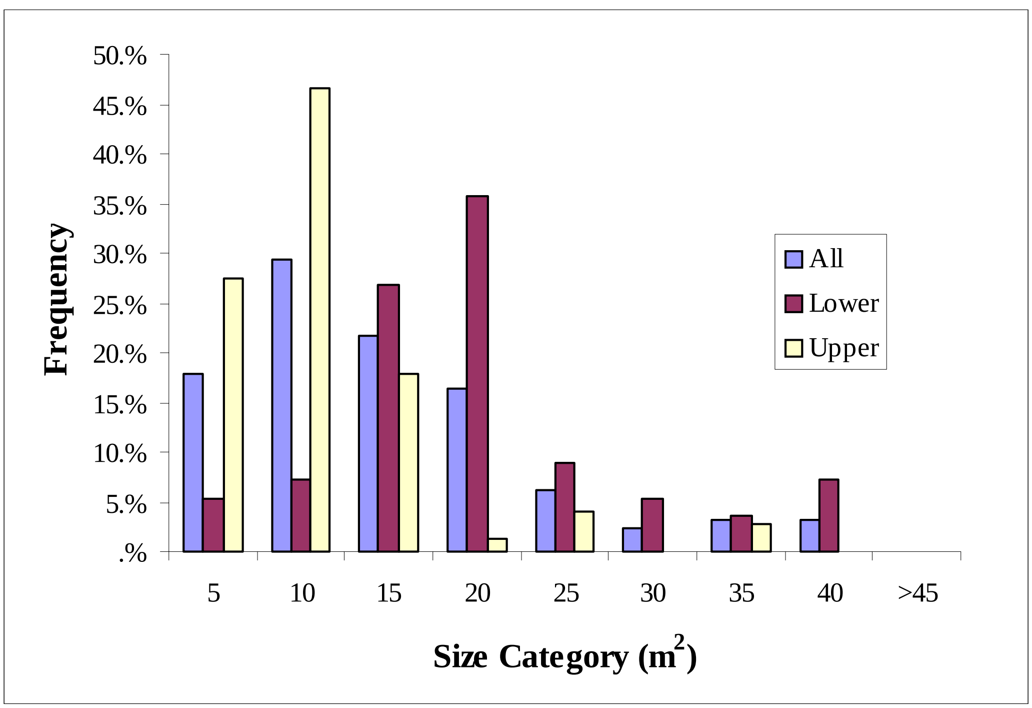

Fig. 6. Histogram of redd areas. The range of redd areas is similar between the upper and lower segments, though the size distribution of the upper segment redds is skewed towards the left.

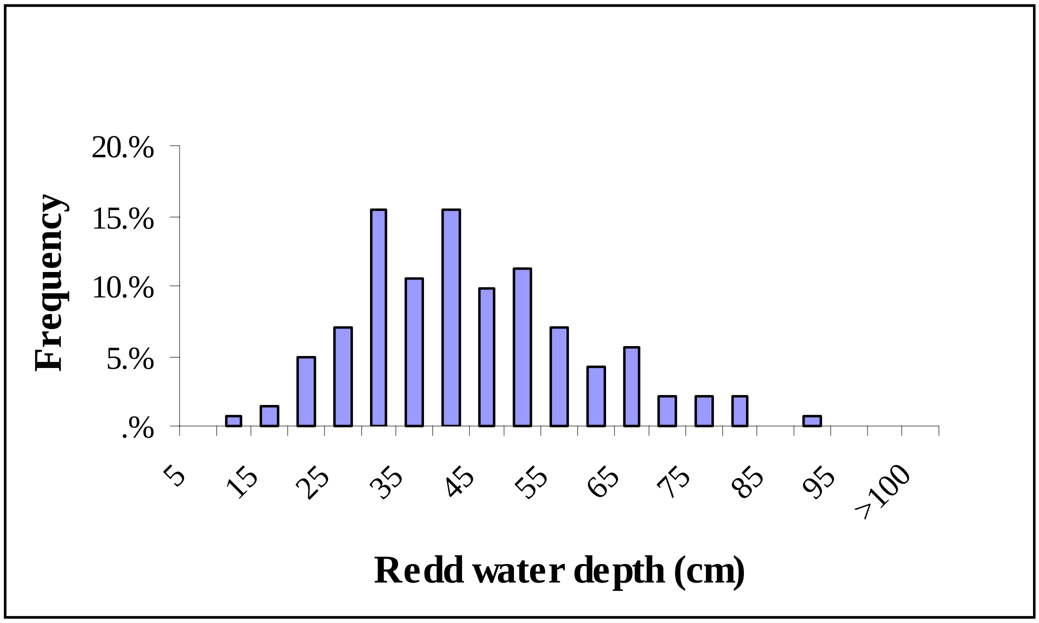

Fig. 7. Relative distribution of depths (cm) at which redds were found.

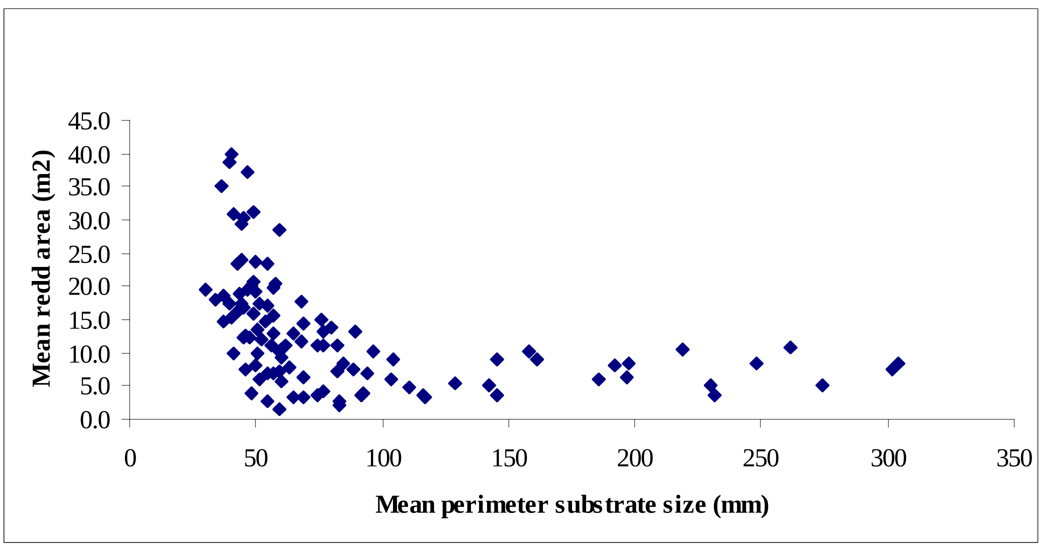

Fig. 9. Mean redd area vs mean perimeter substrate size over the entire range of substrate sizes.

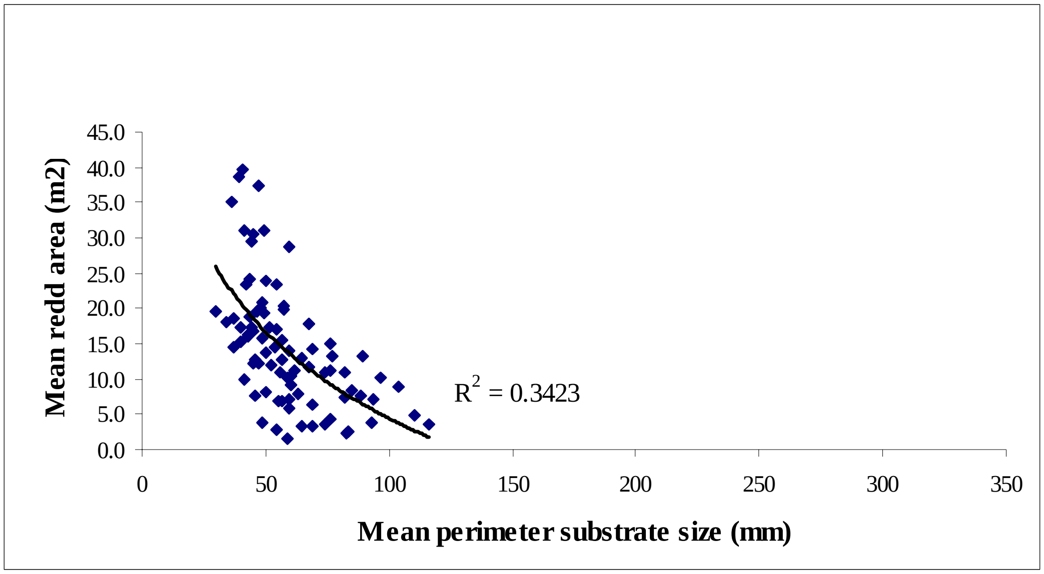

Fig. 10. Mean redd area vs mean perimeter substrate size for mean substrate size less than 125 mm.

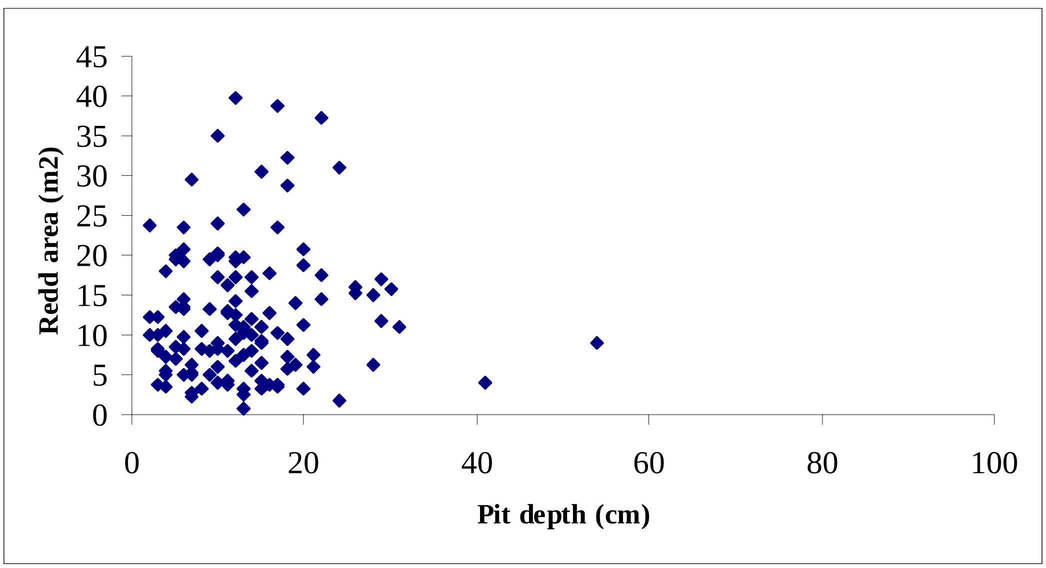

Fig. 11. Redd area vs pit depth.

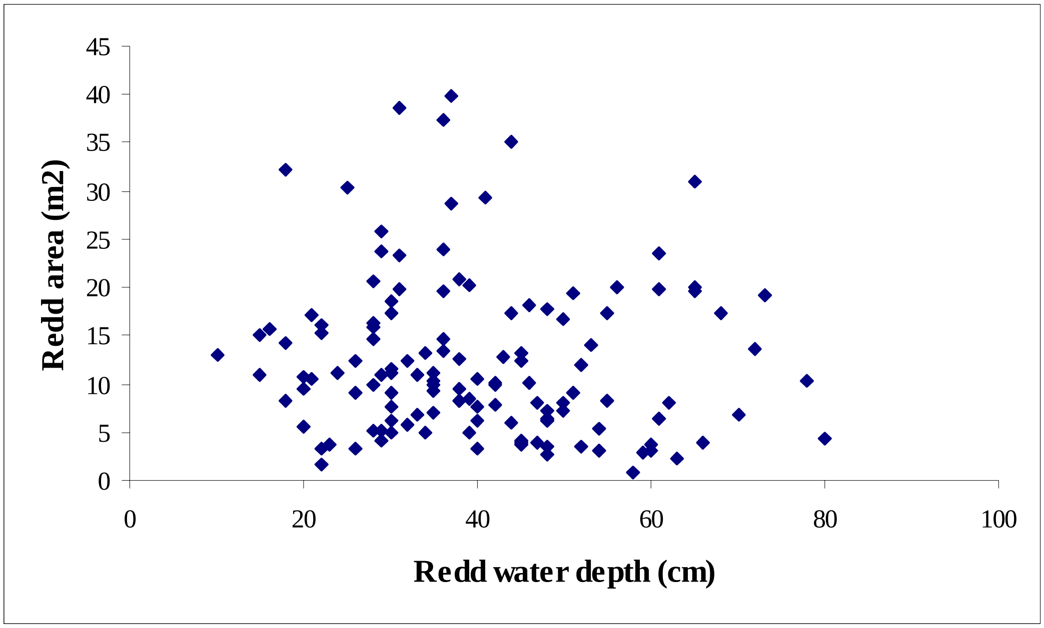

Fig. 12. Redd area vs redd water depth.

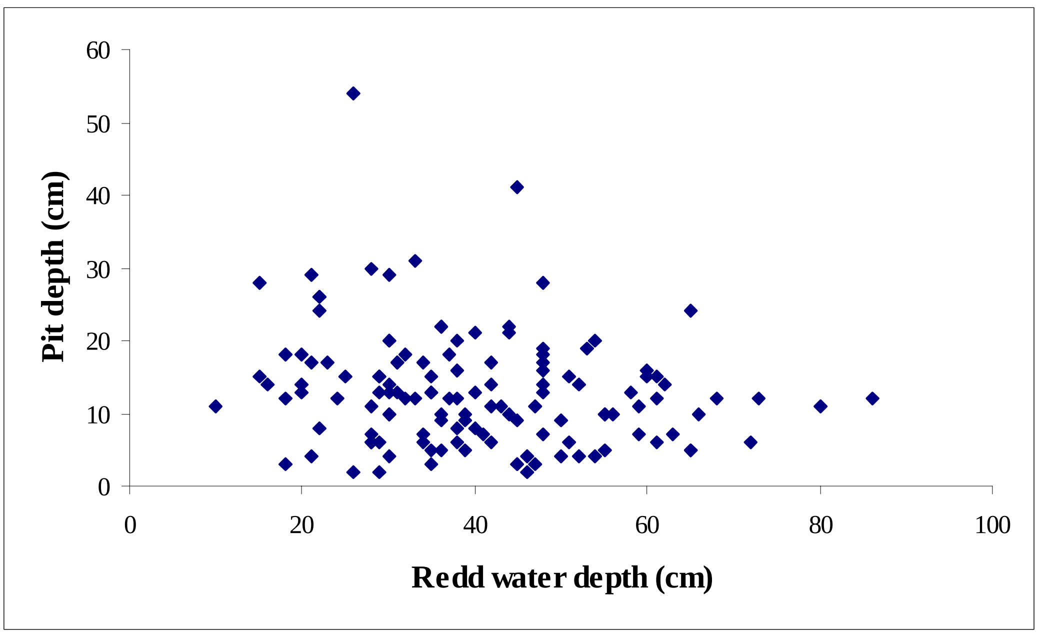

Fig. 13. Pit depth vs redd water depth.

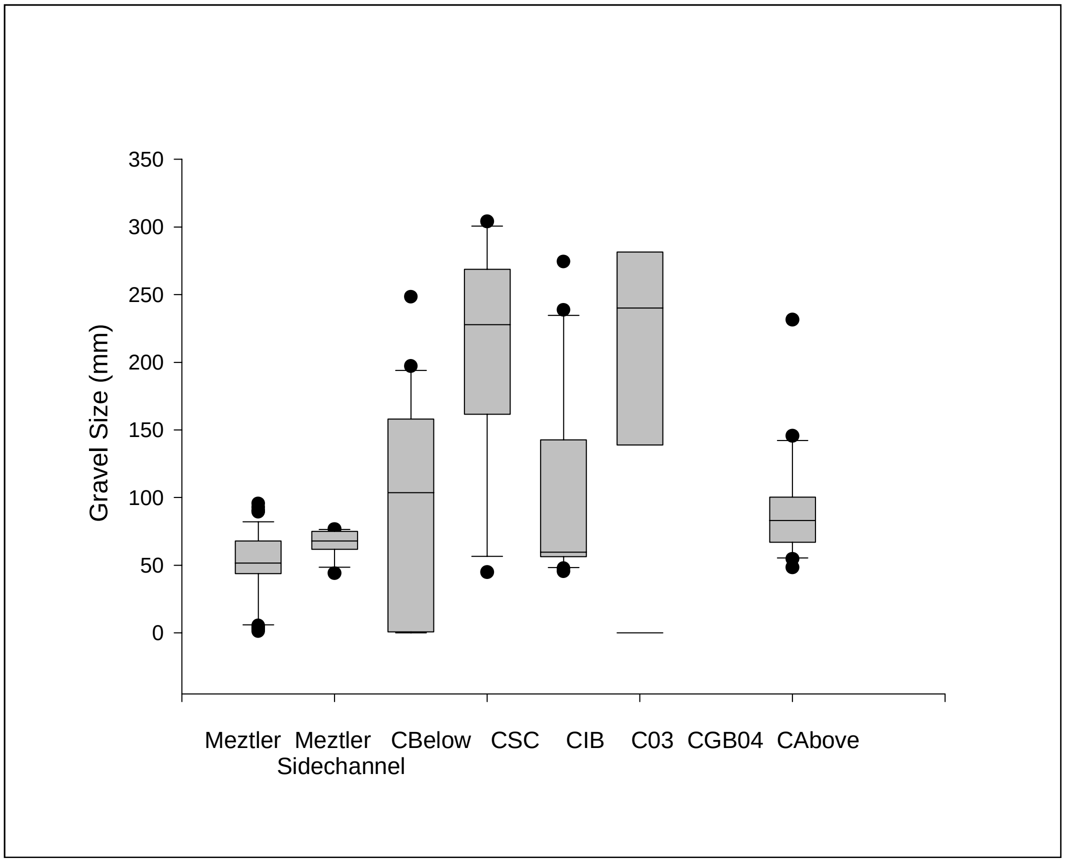

Fig 14. Size distribution for pooled substrate sizes for all redds by reach.

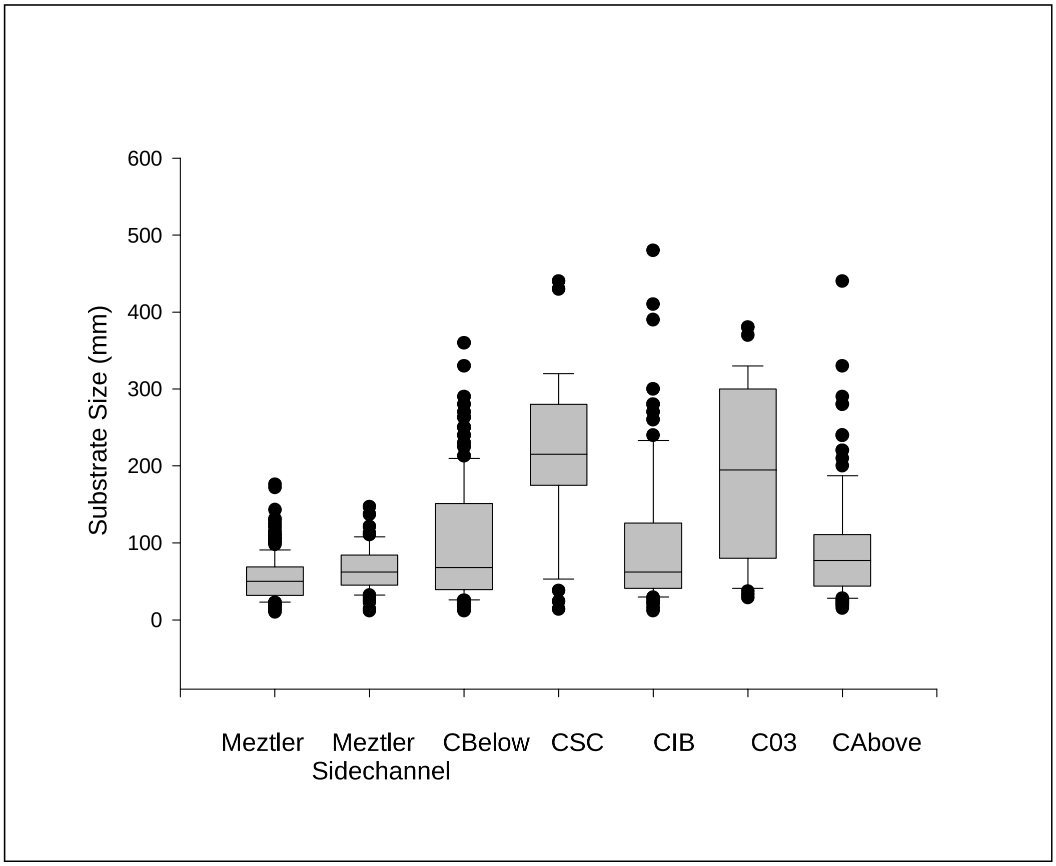

Fig 15. Size distribution of individual particle sizes for all redds by reach.

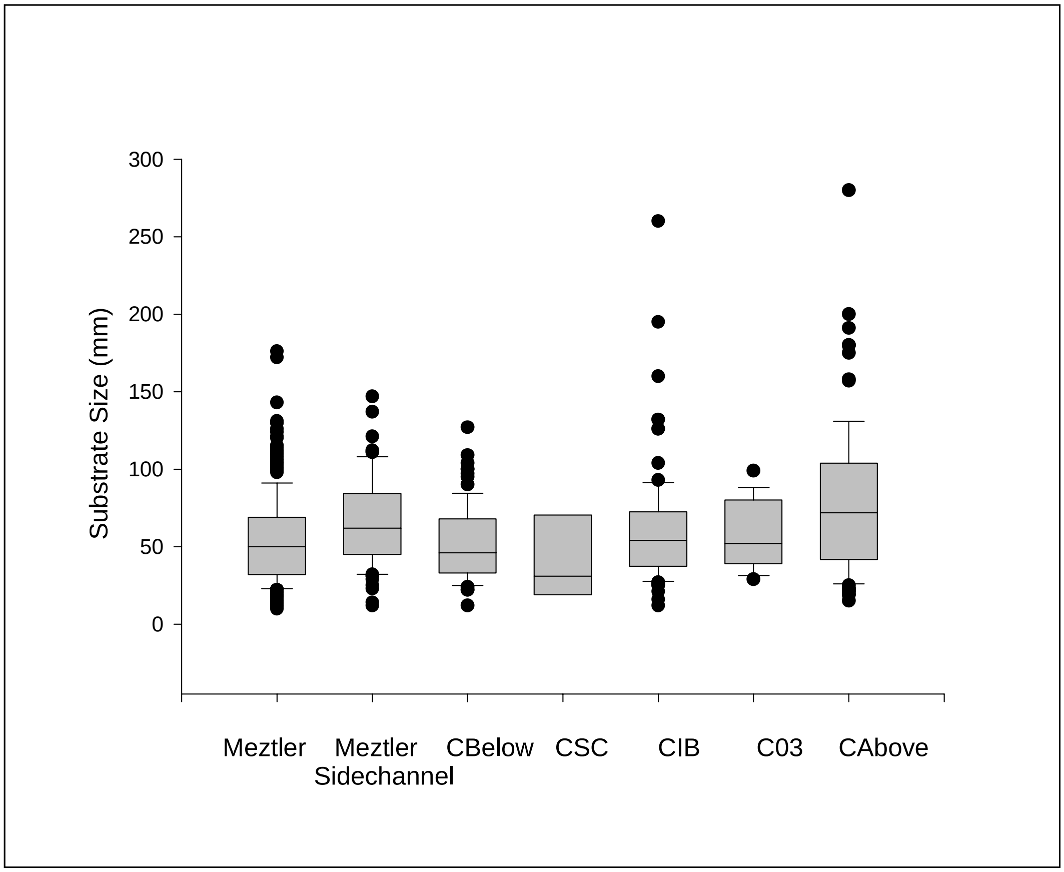

Fig 16. Size distribution of unconfined redds individual particles by reach.

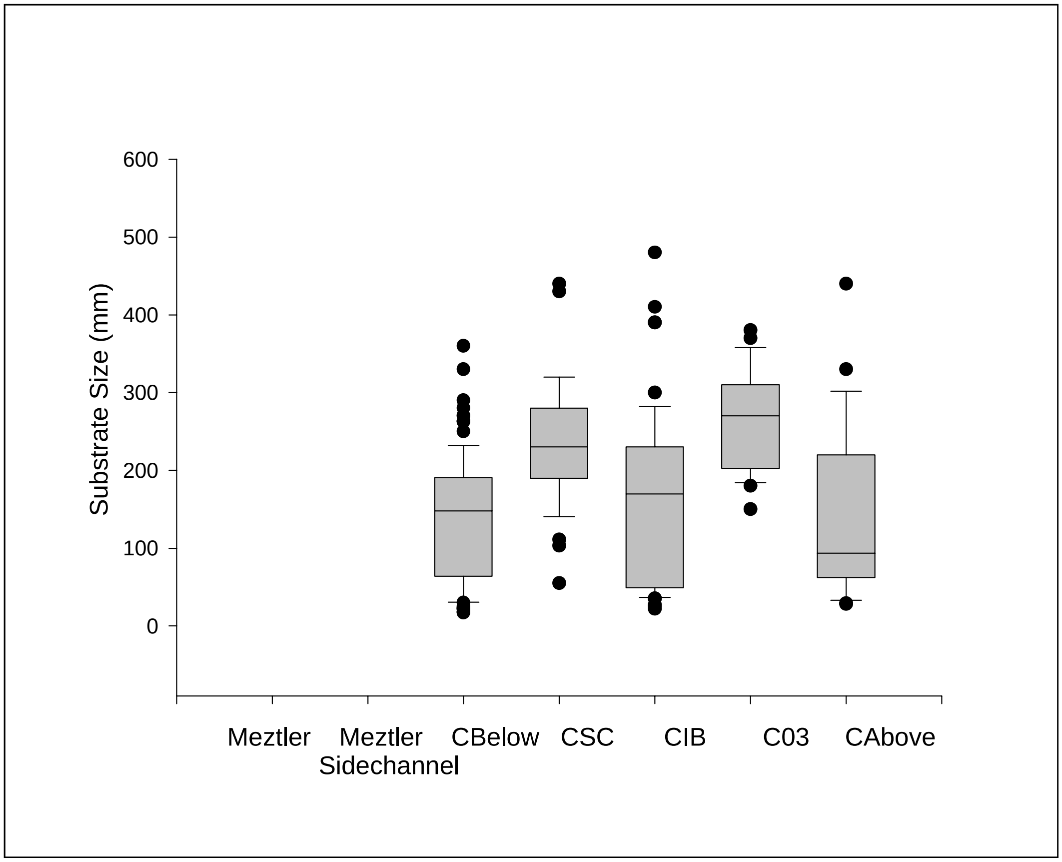

Fig 17. Confined gravel individual particle sizes